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(54) **VISUAL QUALITY MEASURE FOR REAL-TIME VIDEO PROCESSING**

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(51) **Int. Cl.**

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H04N 19/176	(2014.01)
H04N 19/147	(2014.01)
H04N 19/103	(2014.01)

(52) **U.S. Cl.**

CPC ***H04N 19/154*** (2014.11); ***H04N 19/103*** (2014.11); ***H04N 19/147*** (2014.11); ***H04N 19/176*** (2014.11)

(58) **Field of Classification Search**

CPC . H04N 19/103; H04N 19/147; H04N 19/154; H04N 19/176

See application file for complete search history.

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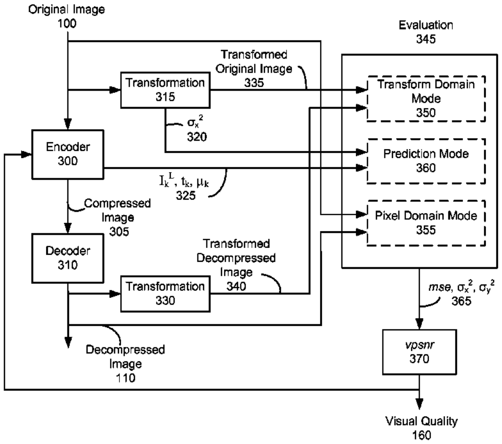
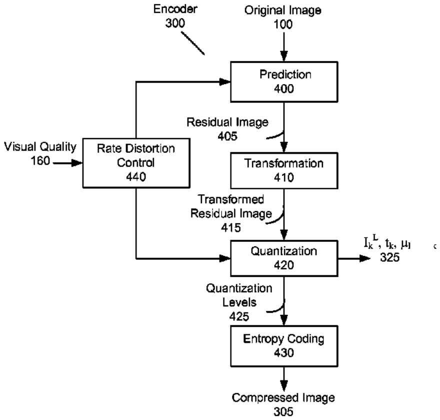
(57) **ABSTRACT**

A measure of visual quality of processed images relative to unprocessed images is generated in real-time. The measure of visual quality closely correlates with a human's actual perception of the processed image relative to the original image. The measure of visual quality is computed based on a measure of discrepancy (e.g., mean square errors) between the processed and unprocessed images and the variance of each image in the pixel domain or the transform domain may be determined. If the processed image is unavailable, a prediction of the processed image may be used in place of the processed image. The prediction of a processed image may involve predicting the variance values for processed image blocks. The visual quality measure may be used in a feedback loop to improve processing or encoding.

20 Claims, 7 Drawing Sheets





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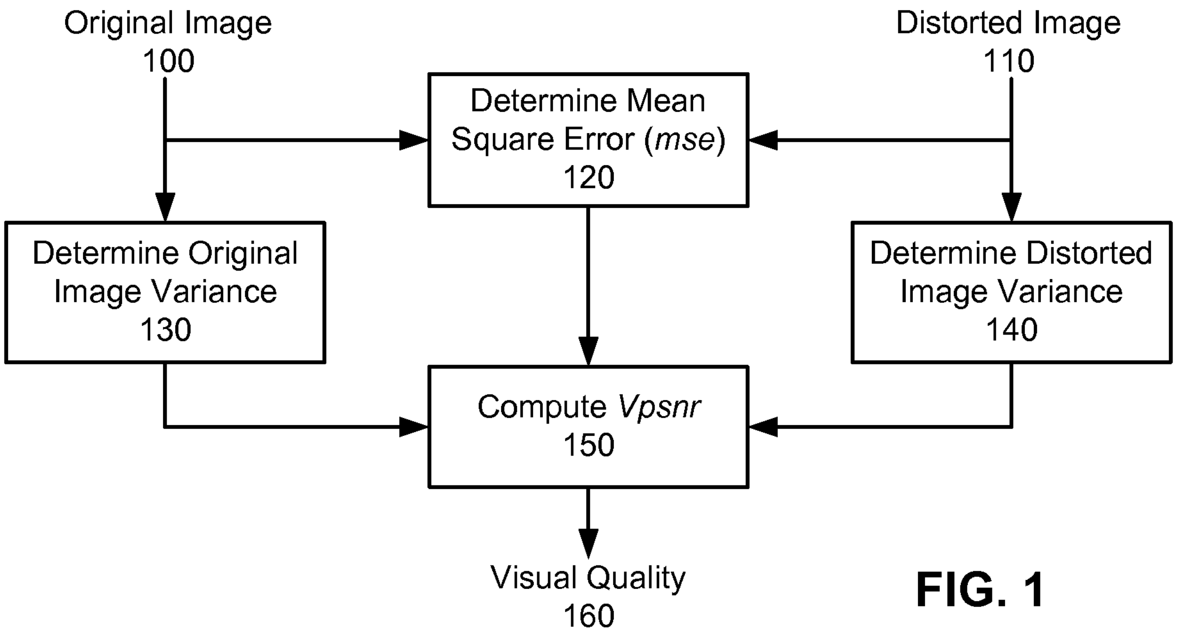
Original Image
100
Distorted Image
110
Determine Mean
Square Error (*mse*)
120
Determine Original
Image Variance
130
Determine Distorted
Image Variance
140
Compute *Vpsnr*
150
Visual Quality
160

FIG. 1

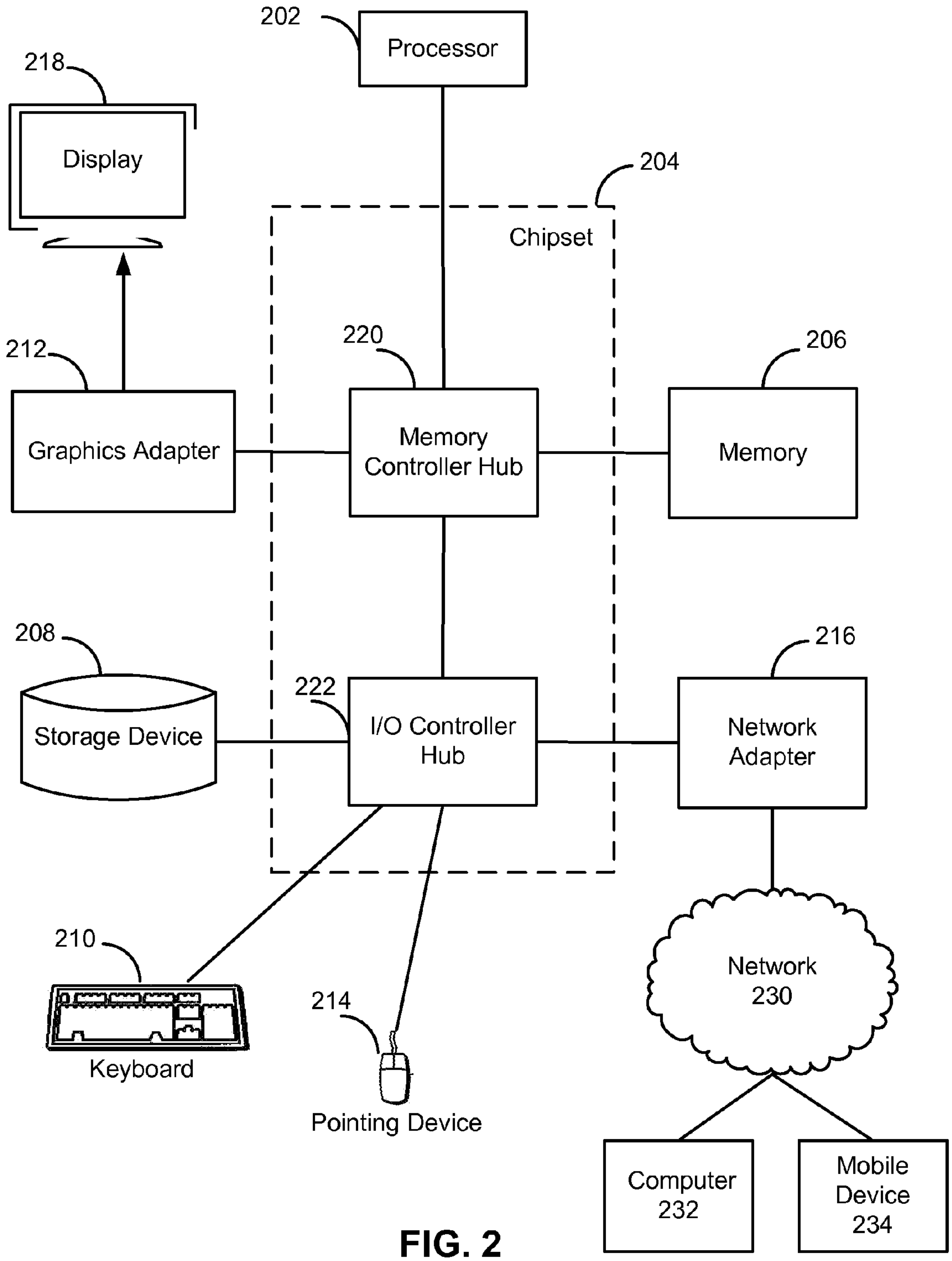
202
Processor
218
Display
204
Chipset
212
220
206
Graphics Adapter
Memory Controller Hub
Memory
208
216
222
Storage Device
I/O Controller Hub
Network Adapter
210
Network 230
214
Keyboard
Pointing Device
Computer 232
Mobile Device 234

FIG. 2

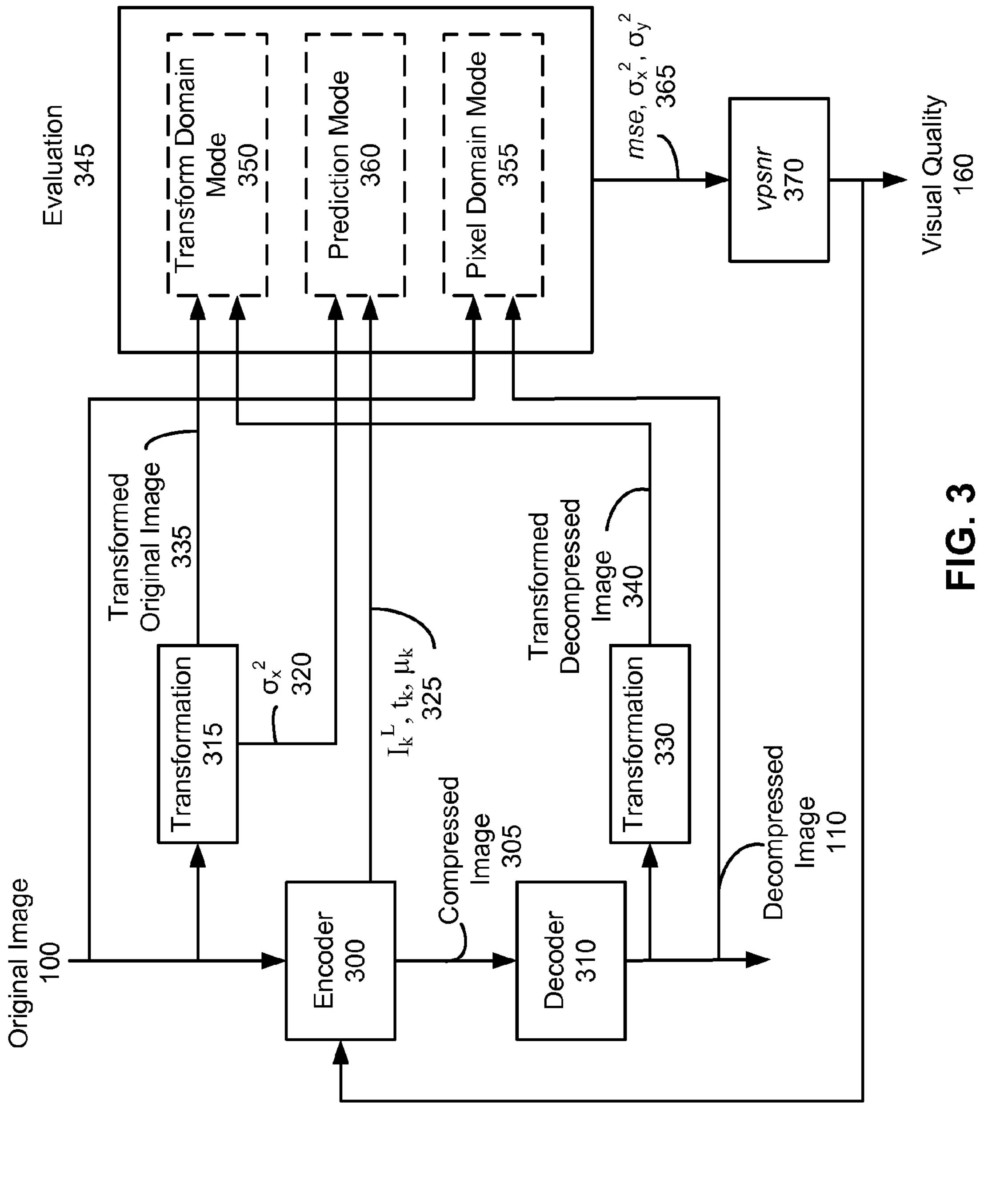
Original Image 100
Encoder 300
Compressed Image 305
Decoder 310
Decompressed Image 110
Transformation 315
Transformation 330
σ_x^2 320
I_k^L, t_k, μ_k 325
Transformed Original Image 335
Transformed Decompressed Image 340
Evaluation 345
Transform Domain Mode 350
Prediction Mode 360
Pixel Domain Mode 355
mse, σ_x^2, σ_y^2 365
$vpsnr$ 370
Visual Quality 160

FIG. 3

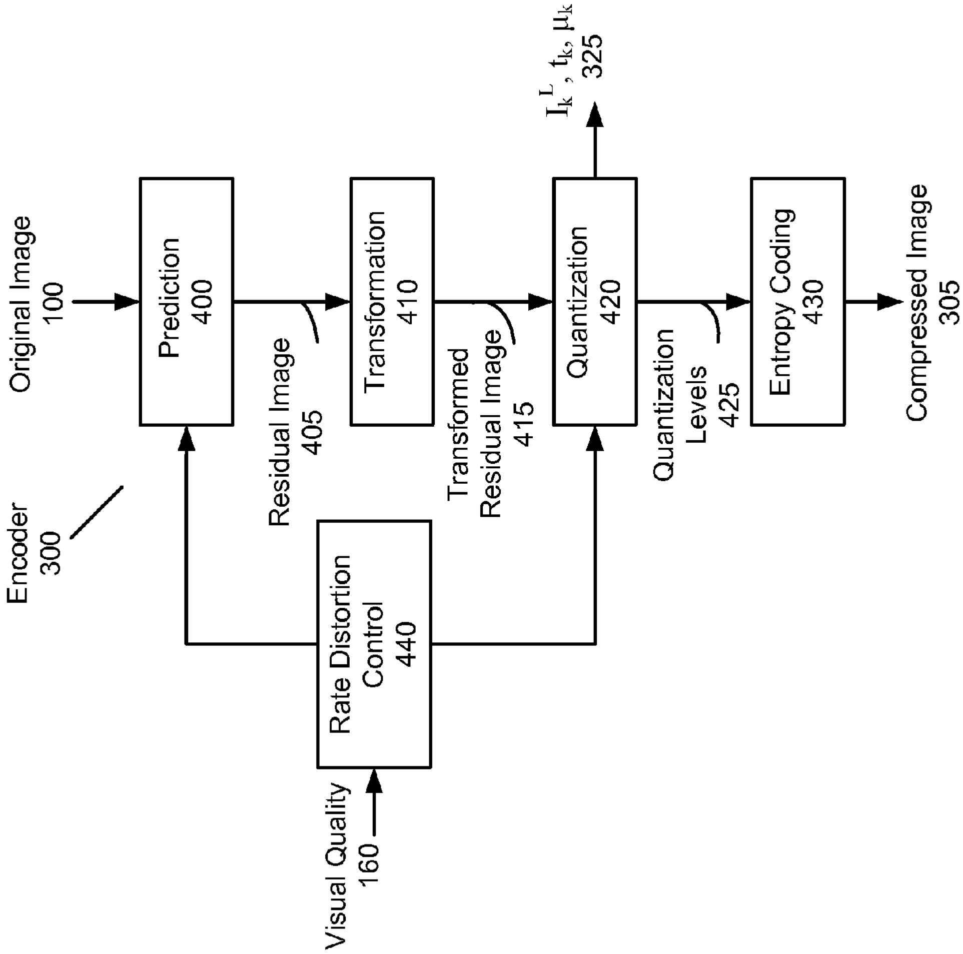
Encoder
300
Original Image
100
Prediction
400
Residual Image
405
Transformation
410
Transformed
Residual Image
415
Quantization
420
I_k^L, t_k, μ_k
325
Quantization
Levels
425
Entropy Coding
430
Compressed Image
305
Rate Distortion
Control
440
Visual Quality
160

FIG. 4

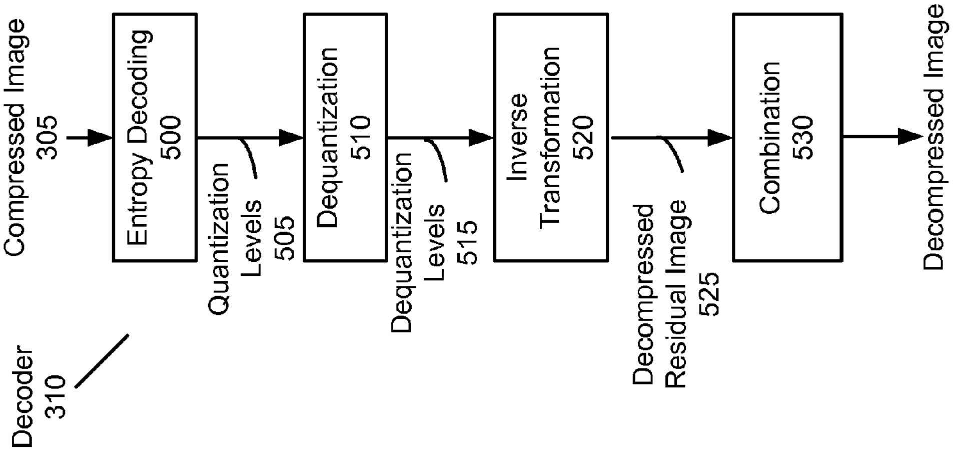
Decoder
310
Compressed Image
305
Entropy Decoding
500
Quantization
Levels
505
Dequantization
510
Dequantization
Levels
515
Inverse
Transformation
520
Decompressed
Residual Image
525
Combination
530
Decompressed Image
120

FIG. 5

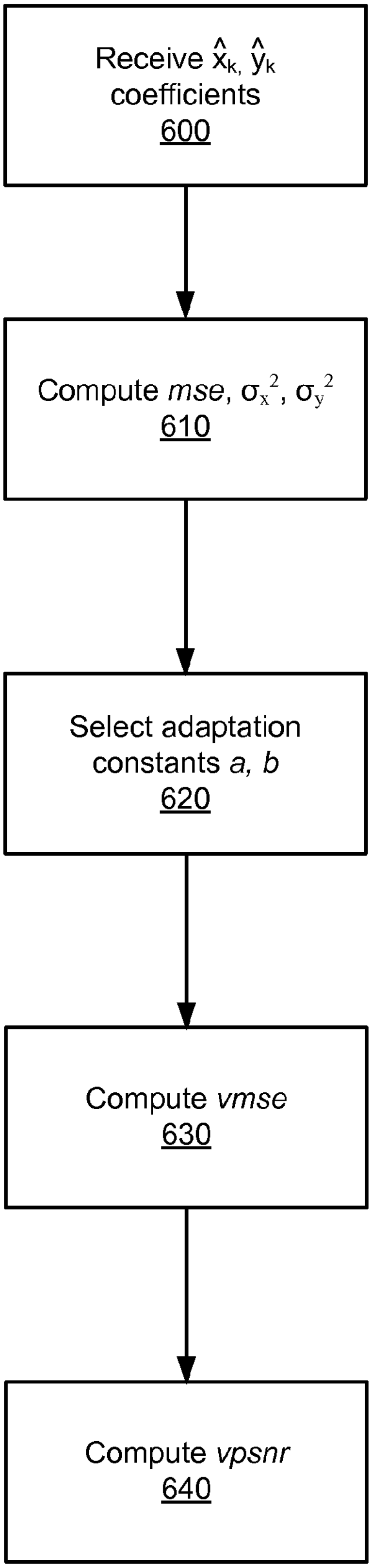
Receive $\hat{x}_k$, $\hat{y}_k$ coefficients
600
Compute *mse*, σ_x^2, σ_y^2
610
Select adaptation constants *a, b*
620
Compute *vmse*
630
Compute *vpsnr*
640

FIG. 6

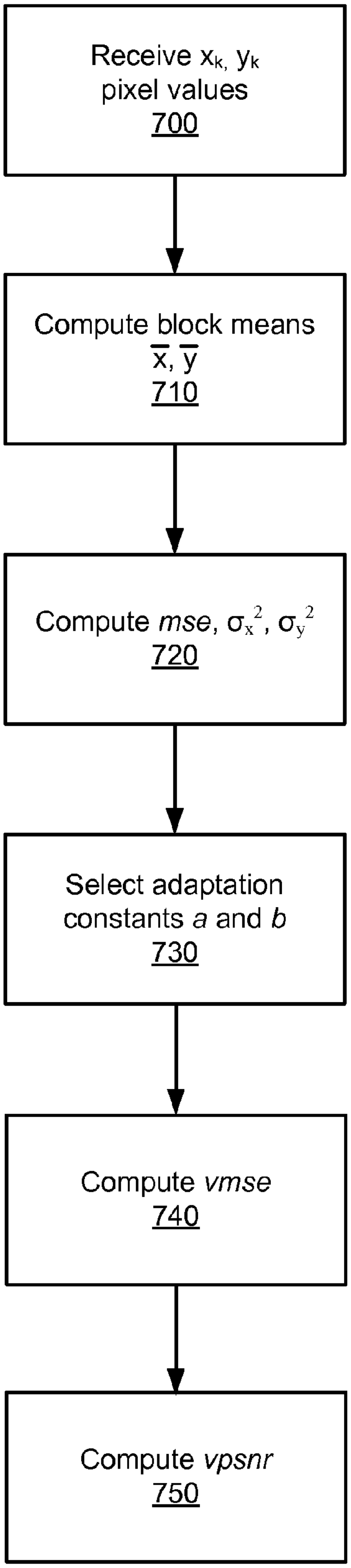
Receive x_k, y_k pixel values
700
Compute block means
$\overline{x}$, $\overline{y}$
710
Compute *mse*, σ_x^2, σ_y^2
720
Select adaptation constants *a* and *b*
730
Compute *vmse*
740
Compute *vpsnr*
750

FIG. 7

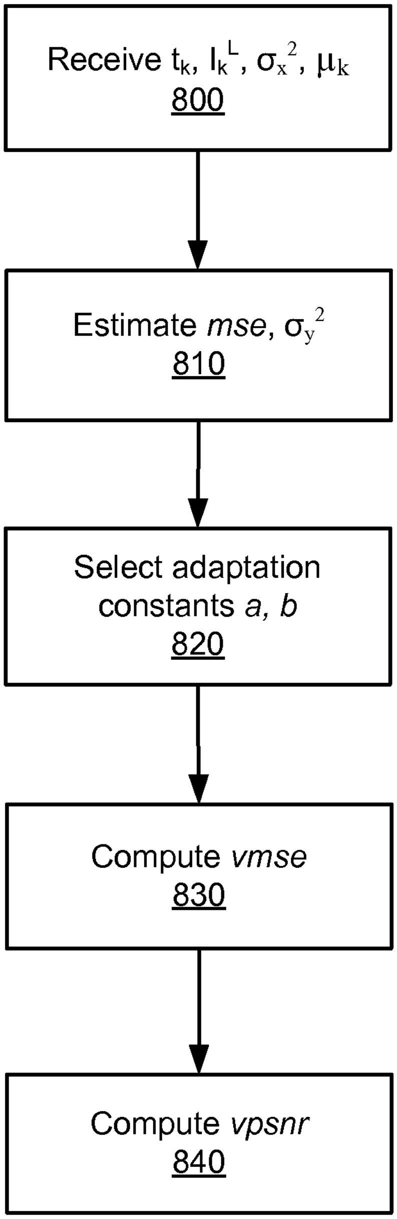
Receive t_k, I_k^L, σ_x^2, μ_k
800
Estimate *mse*, σ_y^2
810
Select adaptation constants *a, b*
820
Compute *vmse*
830
Compute *vpsnr*
840

FIG. 8

VISUAL QUALITY MEASURE FOR REAL-TIME VIDEO PROCESSING

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the right of priority based on Russian application serial no. 2011140632, filed Oct. 6, 2011, which is incorporated by reference in its entirety. This application is related to U.S. patent application Ser. No. 13/448,224, titled "Rate Distortion Optimization in Image and Video Encoding", filed on Apr. 16, 2012, which in turn claims the right of priority based on Russian application serial no. 2011140631, filed Oct. 6, 2011, both of which are incorporated by reference herein in their entirety.

BACKGROUND

1. Field of Disclosure

This disclosure relates in general to the field of digital video and in particular to the objective measurement of digital video quality and the implementation of the measurement in a real time video codec.

2. Description of the Related Art

Raw digital video streams often consume immense digital storage space, and are prohibitively massive for transmission. To reduce storage space or transmission bandwidth requirements, a raw video stream is encoded to reduce its size. Typical video encoding involves the process of subtracting a reference frame from an original frame of video to obtain a residual frame containing less information than the original frame. Residual frames are then further processed to obtain a compressed digital video stream for transmission or storage. A typical video decoder receives the compressed digital video stream and decompresses the compressed digital video into the original video stream or a downgraded version of the digital video stream.

In the field of video coding, the real-time estimation of the visual quality of previously encoded video frames in a compressed video stream is an important consideration in encoding subsequent video frames in the same video stream. The visual quality of encoded video is an objective measure of how the encoded video appears to a viewer. Poor video visual quality is characterized by an image display that appears unnatural to human perception. Examples of instances of poor video visual quality include compression artifacts (e.g., blocking, contouring, mosquito noise, and "digitized" video appearance), discoloration, inconsistent contrasting, and inconsistent resolution display. The visual quality of encoded video can be improved by altering the encoding and compression process if the video encoder detects the poor visual quality of previously encoded video frames. Determining the visual quality of encoded video frames in real-time may help an encoder in effectively improving the visual quality of encoded video.

One common method of measuring encoded video frame visual quality is to determine the peak signal-to-noise ratio (psnr) of the frame. psnr is a non-ideal solution, because although psnr can be computed real-time, psnr correlates poorly with human perception. Other measures, such as the structural similarity index metric (ssim), visual information fidelity (vif), and the multi-scale structural similarity index metric (mssim) cannot practicably be computed in real-time due to their computational complexity, limiting their usefulness in distortion control feedback applications of video

encoders. In addition, ssim, vif, and mssim can only be computed in the pixel domain, furthering limiting their utility.

SUMMARY

Embodiments relate to a method and system for measuring the visual quality of a processed image. A processed image is received, and a measure of discrepancy is determined between a part of the processed image and a corresponding part of a corresponding unprocessed image. The measure of discrepancy may be a mean square error. Variance information is determined for the processed image and for the unprocessed image. A measure of the visual quality of the processed image is then determined based on the measure of discrepancy and the variance information.

In one embodiment, visual quality is measured for more than one part of a processed image and averaged to determine the measure of visual quality of the entire processed image. In one embodiment, visual quality is based on adaptation constants which are selected to increase correlation between the measure of visual quality and human perception. The measure of discrepancy and the variances may be determined in the pixel domain or in the transform domain, or may be predicted in the event that the processed image is unavailable. The measure of visual quality may be used in a feedback loop by an image processor to alter the processing of subsequent images in a video sequence.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a flowchart illustrating a method of determining the visual quality of an encoded video frame using Visual Peak Signal-to-Noise Ratio (vpsnr), according to one embodiment.

FIG. **2** is a high-level block diagram illustrating a typical environment for determining the visual quality of encoded video using vpsnr, according to one embodiment.

FIG. **3** is a high-level block diagram illustrating an environment for determining and applying a visual quality measure in a real time video codec in a transform domain mode, a pixel domain mode, or a prediction mode, according to one embodiment.

FIG. **4** is a block diagram illustrating a detailed view of modules within an encoder module according to one embodiment.

FIG. **5** is a block diagram illustrating a detailed view of modules within a decoder module according to one embodiment.

FIG. **6** is a flowchart illustrating a method of determining the visual quality of video in the transform domain, according to one embodiment.

FIG. **7** is a flowchart illustrating a method of determining the visual quality of video in the pixel domain, according to one embodiment.

FIG. **8** is a flowchart illustrating a method of determining the visual quality of video in a prediction mode, according to one embodiment.

DETAILED DESCRIPTION

The Figures (FIGS.) and the following description describe certain embodiments by way of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles described herein. Reference will now be made in detail to several embodiments, examples of which are illustrated in the accompanying figures. It is noted that wherever practicable similar or like reference numbers may be used in the figures and may indicate similar or like functionality.

Embodiments relate to generating a measure of visual quality of processed images relative to unprocessed images in real-time. The measure of visual quality closely correlates with a human's actual perception of the processed image relative to the original image. The measure of visual quality is computed based on a measure of discrepancy (e.g., mean square errors) between the processed and unprocessed images and the variance of each image in the pixel domain or the transform domain may be determined. If the processed image is unavailable, a prediction of the processed image may be used in place of the processed image. In one embodiment, a prediction of a processed image comprises predictions of the variance values for processed image blocks. The visual quality measure may be used in a feedback loop to improve processing or encoding.

Processing of images described herein includes encoding digital video frames. Such processing may involve, for example, lossy compression that may result in a processed image non-identical to or of poorer quality than a corresponding original image. The visual quality measure described herein refers to an index or parameter indicative of the level of distortion in a displayed image relative to the original image perceivable to a viewer. In the context of determining the visual quality of an encoded video frame, reference to both an original image and a distorted image implies the association that a particular distorted image is the result of encoding and decoding a particular original image. Further, reference to the visual quality of "encoded video" refers both to a single encoded video frame, or multiple encoded video frames.

Video frames described herein refer to images that when displayed consecutively form motion video. The video frames may be referred to as either frames or images interchangeably. Video frames that have undergone encoding may be referred to as either encoded or compressed video frames. Video compression often results in the loss of video data, and thus decompressed frames may be referred to as distorted frames herein.

A block described herein refers to a group of pixels within an image in a spatial pixel domain or a group of coefficients in a transform domain. In a spatial pixel domain, a block may include information about luminance or chrominance values for a set of pixels. A block may be a group of pixels of any size (e.g., 4×4 pixels or 8×8 pixels) in the spatial pixel domain. In a transform domain, blocks may be a group of transform coefficients of any size within an image. Block size in both pixel and transform domains may be dependent on the size of the transform applied to an image. Blocks may vary in size within a single image, or may be constant in size.

Pixel domain as described herein implies operations on or functionality involving images which may be represented by spatial pixel information. The term "pixel mode" implies operation or functionality within the spatial pixel domain. Transform domain as described herein implies operations on or functionality involving images which have undergone transformation from the spatial pixel domain into another domain, such as the frequency domain, and which may be represented by coefficient information. The term "transform mode" implies operation or functionality within the transform domain. Prediction mode as described herein implies operation or functionality external to encoding and decoding which estimates the visual quality of encoded video independently of the method or process used to produce the encoded video.

Overview of Process for Computing Visual Quality

FIG. **1** is a flowchart illustrating a method of determining the visual quality of an encoded video frame using Visual Peak Signal-to-Noise Ratio (vpsnr), according to one embodiment. In the embodiment of FIG. **1**, the visual quality **160** of distorted image **110** relative to original image **100** is determined based on a series of computations. In one embodiment, where the distorted image **110** is not available, an estimation or prediction of the distorted image **110** may be used instead in determining the visual quality measure **160** between two video frames. The series of computations include determining **120** the mean square error (mse) of the original image and the distorted image.

An mse generally is a measure of discrepancy quantifying the difference between an estimator and the actual value of the quantity being estimated. The mse in the context of images comprises the average of the squared difference between an estimator image (e.g., the distorted image **110**) and the actual image being estimated (e.g., the original image **100**). The mse between non-overlapping corresponding blocks in the two images may be determined **120** in the spatial pixel domain or the transform domain. In instances where a distorted image **110** is not available, the mse may be determined **120** by using other methods, discussed below in detail with regards to FIGS. **3** and **8**. The mse may be determined **120** for an entire image, for one or more blocks within an image, or for every block within an image.

The series of computations also include determining **130** the variance of blocks in the original image **100** (hereinafter referred to as "the variances of the original image"), and determining **140** the variance of blocks in distorted image **110** (hereinafter referred to as "the variances of the distorted image"). A variance generally is a measure of how widely distributed a set of information or data is. Variance may be determined by averaging the squared deviation of data from the mean of the data's distribution for each individual datum in the set of data. In the context of images, variance may be a measure of the extent of distribution of any characteristic or property of an image block. For instance, the variance may be determined for the color distribution of a block, the brightness of the block, the contrast of the block, or any other image block property. Further, the variance for an image block may be determined in the pixel domain or the transform domain.

If the distorted image **110** is not available, the variances for the distorted image **110** may be determined **140** by using other methods, discussed below in detail with regards to FIG. **3** and FIG. **8**. The variances of an image may be determined for an entire image, for one or more blocks within an image, or for every block within an image. In the examples described below in detail with reference to equations (1) through (13), the variances may be determined for every non-overlapped block within the image.

After the mse is determined, the variances of the original image and the variances of the distorted image are determined, the Visual Peak Signal-to-Noise Ratio ("vpsnr") is computed **150**. The vpsnr is computed **150** based on the Visual Mean Squared Error ("vmse"), which is computed based on the mse, the variances of the original image, and the variances of the distorted image, and may be computed based on adaptation constants, which are discussed below in greater detail in regards to FIGS. **6** through **8**. The vmse may be computed for the entirety of the original image **100** and the distorted image **110**, or for one or more blocks or portions of original image **100** and distorted image **110**.

In one embodiment, the process of computing **150** vpsnr includes computing the vmse for each of the plurality of blocks of the original image **100** and the corresponding blocks of the distorted image **110**, and averaging the computed vmse values. Alternatively, the vpsnr may be computed **150** by computing the vmse for a subset of the plurality of blocks of the original image **100** and the corresponding blocks of the distorted image **110**. The output of the method is the visual quality **160** of the distorted image **110** relative to the original image **100**. The visual quality **160** may be a unit-less ratio of distortion between the distorted image **110** and the original image **100**, or may comprise any suitable measurement unit.

vpsnr may be computed in real-time, unlike alternative methods of determining visual quality. Further, as is noted in Table 1 below, vpsnr correlates with human perception better than many alternative methods of determining visual quality. Finally, vpsnr allows the flexibility of determining a measure of visual quality of processed images in the pixel mode, the domain mode, or in circumstances where the processed image is unavailable.

Example Operating Environment

FIG. **2** is a high-level block diagram illustrating a typical environment for determining the visual quality of encoded video using vpsnr, according to one embodiment. Illustrated are at least one processor **202** coupled to a chipset **204**. Also coupled to the chipset **204** are a memory **206**, a storage device **208**, a keyboard **210**, a graphics adapter **212**, a pointing device **214**, and a network adapter **216**. The network adapter **216** is communicatively coupled to computer **232** and mobile device **234** through network **230**. A display **218** is coupled to the graphics adapter **212**. In one embodiment, the functionality of the chipset **204** is provided by a memory controller hub **220** and an I/O controller hub **222**.

In another embodiment, the memory **206** is coupled directly to the processor **202** instead of the chipset **204**, or is located within processor **202**, such as in a system-on-a-chip environment. In such embodiments, the operating environment may lack certain components, such as chipset **204**, storage device **208**, keyboard **210**, graphics adapter **212**, pointing device **214**, network adapter **216** and display **218**. Processor **202** may be a special-purpose dedicated processor, such as an Application-Specific Integrated Circuit (ASIC), or a customizable general-purpose processor, such as a Field-Programmable Gate Array (FPGA). Processor **202** may also be embodied as a commercially available Central Processing Unit (CPU) or (Graphics Processing Unit (GPU), with one or more processor cores.

The storage device **208** is a non-transitory computer-readable storage medium, such as a hard drive, compact disk read-only memory (CD-ROM), DVD, or a solid-state memory device. The memory **206** may contain, among other data, instructions and data used by the processor **202**. The pointing device **214** is a mouse, track ball, or other type of pointing device, and is used in combination with the keyboard **210** to input data into the computer system. The graphics adapter **212** displays images and other information on the display **218**. The network **230** enables communications between the processor **202**, computer **232** and mobile device **234**. In one embodiment, the network **230** uses standard communications technologies and/or protocols and can include the Internet as well as mobile telephone networks.

Additional modules not illustrated in FIG. **2** may also be present in the operating environment. For instance, encoder modules, decoder modules, transform modules, or any other claimed module may be implemented by processor **202**, chipset **204**, memory **206**, storage device **208**, graphics adapter **212**, or by an additional component not displayed such as a specialized hardware module to implement the functionality described below with regards to FIGS. **3** through **8**, which may or may not be external to the computer. This description uses the term "module" to refer to computer program logic for providing a specified functionality. A module can be implemented in hardware, firmware, and/or software. A module is typically stored on a computer-readable storage medium such as the storage device **208**, loaded into the memory **206**, and executed by the processor **202**.

Example Visual Quality Measure Determination and Application Environment

FIG. **3** is a high-level block diagram illustrating an environment for determining and applying the visual quality measure described in FIG. **1** in a real time video codec in a transform domain mode, a pixel domain mode, or a prediction mode, according to one embodiment. The environment of FIG. **3** may include, among other components, encoder **300**, decoder **310**, transformation modules **315** and **330**, evaluation module **345** and vpsnr module **370**. The environment of FIG. **3** may be implemented in, for example, the processor **202** and memory **206** of FIG. **2**, or may be implemented in other components and/or modules In one embodiment, encoder **300** may be implemented in processor **202** and memory **206**, and decoder **310** may be implemented in computer **232** or mobile device **234**.

The encoder **300** of FIG. **3** receives an original image **100** from a storage medium or transmission interface, encodes the image (as described below in detail with regards to FIG. **4**), and outputs a compressed image **305**. The decoder **310** receives the compressed image **305** and decodes the image (as described below in detail with regards to FIG. **5**), and outputs a decompressed image **110**. In one embodiment, the encoder **300** and decoder **310** are implemented in the same processor, module, integrated circuit or computer. Alternatively, the encoder **300** and decoder **310** may be implemented in different computers or systems, and the compressed image **305** is transmitted via network **230**. In such an embodiment, there may be more than one decoder; for instance, an encoding device may contain a decoder for feedback or distortion control and may transmit encoded video to a separate decoder for decoding and display. In one embodiment encoder **300** receives visual quality measure **160** and performs rate distortion control or other similar feedback techniques which may be used to alter the quality of encoded video based at least in part on the received visual quality measure **160**.

The evaluation module **345** determines the mean square error (mse) between a coded image and an original image, the variances of an original image (σ_x^2), and the variances of a decompressed image (σ_y^2). In one embodiment, the evaluation module **345** may operate in one or more different modes, such as a transform domain mode **350**, a pixel domain mode **355**, and a prediction mode **360**. These modes will be discussed below in greater detail with respect to FIGS. **6** through **8**. In one embodiment, the evaluation module **345** operates in a single mode. In one embodiment, multiple evaluation modules may be used, each operating in a separate mode. Alternatively, the evaluation module **345** may operate in more than one mode simultaneously, providing more than one visual quality measure **160** simultaneously. In one embodiment, an evaluation module **345** may comprise separate modules for mse and variance determination functionality.

The evaluation module **345** may request and receive various inputs depending on the operating mode. For instance, the original image **100** and the decompressed image **110** may be transmitted to evaluation module **345**. The original image **100** and decompressed image **110** may be provided in the form of pixels for an entire image, in the form of image blocks comprising pixels, in the form of image sub-blocks comprising one or more portions of an image block, or in any other form. In another embodiment, the transformed original image **335** and the transformed decompressed image **340** are transmitted to evaluation module **345**. The transformed original image **335** and transformed decompressed image **340** may be provided in the form of coefficients for the entire image, in sets of coefficients, where each set represents an image block, or in any other format.

In one embodiment, variances σ_x^2 **320** (described below in detail with reference to equations (2) and (7)), and standard deviations of image block coefficients μ_k, quantization invariants I_k^L, and quantization thresholds t_k **325** (described below with regards to FIG. **8**) may be transmitted to evaluation module **345**. Variances σ_x^2 **320** and transformed original image **335** may be provided by transformation module **315**. Transformation module **315** may be external or internal to encoder **300**. For instance, encoder **300** may have a transformation module used in encoding which may provide the required values. Alternatively, a separate transformation module **315** may be used to separately compute these values. In one embodiment, a separate transformation module **315** may be required for existing encoder hardware or software incapable of separately outputting the required values.

The encoder **300** may produce and/or transmit standard deviations μ_k, quantization invariants I_k^L, and quantization thresholds t_k **325** to evaluation module **345**. Alternatively, these values **325** may be provided by a source external to encoder **300**. Each value **325** may be provided by a different source, or may be provided by the same source. Similarly, transformed decompressed image **340** may be provided by transformation module **330**, which may be external or internal to decoder **310**, or which may be external or internal to encoder **300**. In one embodiment, transformation modules **315** and **330** may be implemented in the same module, or may be implemented with the same hardware or software components. Variances σ_x^2 **320**, and standard deviations μ_k, quantization invariants I_k^L, and quantization thresholds t_k **325** will be discussed in greater detail below.

The vpsnr module **370** receives the determined mse, σ_x^2, and σ_y^2 **365** from the evaluation module **345** and computes the visual quality measure **160**. In one embodiment, the vpsnr module **370** and the evaluation module **345** are implemented in the same module. In one embodiment, the visual quality measure **160** is transmitted to encoder **300**.

Example Encoder and Decoder Architecture

FIG. **4** is a high-level block diagram illustrating an encoder module **300** in detail, according to one embodiment. The encoder module **300** may include, among other components, prediction module **400**, transformation module **410**, quantization module **420**, entropy coding module **430** and rate distortion control module **440**. The functions described herein can be distributed among the modules in accordance with other embodiments in a different manner or by different entities than is described herein.

Prediction module **400** receives an original image **100** and performs image prediction by selecting a prediction image with similar features to the original image and subtracting the prediction image from the original image, resulting in a selected prediction image and a residual image **405**. Image prediction may utilize spatial prediction (identifying objects, shapes, curves, lines, or any other characteristic of the original image similar to a characteristic in a prediction image), temporal prediction (identifying characteristics of frames preceding or following the original image, such as the motion of an object in the original frame), or any other suitable method of image prediction. For example, the prediction module **400** may use motion estimation and/or motion prediction to generate the prediction image as well known in the art.

The transformation module **410** receives the residual image **405** and applies a transform to produce coefficients in a transform domain (e.g., frequency domain). Example transforms may include a Discrete Cosine Transform (DCT) or a wavelet transform. In one embodiment, transformation module **410** produces a set of coefficients for each block of pixels (e.g., 4×4 pixels or 8×8 pixels). In one embodiment, sets of coefficient are produced for non-overlapping blocks of pixels. The transformed residual image **415** may comprise multiple sets of coefficients. For instance, the transformed residual image **415** comprises one set of coefficients for each image block.

Quantization module **420** receives the transformed residual image **415** and compresses the range of coefficient values to a single quantum value. In one embodiment, the transformed residual image **415** coefficients are divided by a selected quantization matrix, Q_k, and the resulting coefficient quotients ("quantization levels" **425**) are rounded to the nearest integer. In one embodiment, a codec may have a set of quantization thresholds t_k and quantization invariants I_k^L, where $I_k^L = L \cdot Q_k$, which are used to determine quantization levels **425**. For instance, for a given transformed residual image **415** coefficient $\hat{r}_k$, where $I_k^L - (1-t_k) \cdot Q_k \leq \hat{r}_k < I_k^{L+1} - (1-t_k) \cdot Q_k$, $\hat{r}_k$ is mapped to quantization level L. Typically, quantization results in many higher frequency coefficients being rounded to zero, reducing the digital footprint of the image. Quantization module **420** may also determine and/or output quantization thresholds t_k and quantization invariants I_k^L. In addition, quantization module **420** may determine and output the standard deviations μ_k of the transformed residual image **415** coefficients.

Entropy coding module **430** receives quantization levels **425** and compresses the quantization levels **425** to form compressed image **305**. Entropy coding module **430** may utilize any lossless compression scheme independent of the specific characteristics of the coding medium. In one embodiment, entropy coding module **430** compresses the quantization levels **425** by replacing each fixed-length coefficient with a variable-length prefix codeword. The prefix codewords may be assigned to coefficient values based on the frequency of occurrence of coefficients. In such a scheme, the most common coefficients may be replaced with the shortest prefix codewords.

The encoder **300** may have a rate distortion control module **440**, which may adjust steps in the encoding process to response to receiving a determined visual quality **160**. For instance, the encoder **300** may determine that visual quality **160** of the compressed image **305** is undesirably low, indicating insufficient or inadequate encoding. Likewise, the encoder **300** may determine that visual quality **160** is unnecessarily high, indicating that fewer resources may be used in the encoding process.

In one embodiment, rate distortion control module **440** determines that the visual quality **160** is below a pre-determined threshold. In this embodiment, rate distortion control module **440** may request that prediction module **400** select a prediction image from a larger collection or library of images. Likewise, rate distortion control module **440** may request that quantization module **420** adjust quantization thresholds t_k

and/or quantization invariants I_k^L in order to preserve more image information when encoding future images. Similarly, rate distortion control module **440** may determine that visual quality **160** is above a pre-determined threshold. In such a situation, rate distortion control module **440** may request that prediction module **400** spend less time selecting a prediction image, or may request that quantization module **420** alter quantization thresholds t_k and/or quantization invariants I_k^L in order to preserve less image information. Additionally, rate distortion control module **440** may also request other modules and/or functionalities of the encoder to alter encoding performance in other ways. Further details of the rate disclosure control may be found in co-pending U.S. patent application Ser. No. 13/448,224, titled "Rate Distortion Optimization in Image and Video Encoding", filed on Apr. 16, 2012, the contents of which are hereby incorporated by reference.

FIG. **5** is a high-level block diagram illustrating a detailed view of modules within a decoder module **310**, according to one embodiment. The decoder may include, among components, entropy decoding module **500**, dequantization module **510**, inverse transformation module **520**, and combination module **530**. The functions described herein can be distributed among the modules in accordance with other embodiments in a different manner or by different entities than is described herein.

Entropy decoding module **500** receives compressed image **305** and performs entropy decoding on the compressed image **305** to produce quantization levels **505**. In one embodiment, entropy decoding is accomplished by replacing prefixed codewords with fixed-length coefficients. Entropy decoding may require receiving a look-up table or other decoding key from encoder **300** or entropy coding module **430**.

Dequantization module **510** receives the quantization levels **505** and produces dequantization levels **515**. In one embodiment, quantization levels **505** are identical to quantization levels **425**. Dequantization module **510** may multiply quantization levels **505** by a selected quantization matrix to produce dequantization levels **515**. In one embodiment, the selected quantization matrices used by quantization module **420** and dequantization module **510** are identical.

Inverse transformation module **520** receives the dequantization levels **515** and produces the decompressed residual image **525**. The dequantization levels **515** are image coefficients for the transform domain decompressed residual image, and the decompressed residual image **525** is a pixel domain image, and comprises pixel information. In one embodiment, the inverse transformation module **520** applies a DCT-related inverse transform to the dequantization levels **515**.

Combination module **530** receives the decompressed residual image **525** and retrieves the associated prediction image. In one embodiment, the associated prediction image is a previously decoded image, and the encoder **300** transmits the location of the prediction image to the decoder **310**. Combination module **530** combines the decompressed residual image **525** and retrieved prediction image to produce the decompressed image **120**. The combination of the decompressed residual image **525** and the retrieved prediction image may comprise adding color values between a particular decompressed residual image **525** pixel and an associated prediction image pixel for each pixel in the decompressed residual image **525**.

Example Visual Quality Determination

FIG. **6** is a flowchart illustrating a method of determining the visual quality of video in the transform domain, according

to one embodiment. In one embodiment, the method of FIG. **6** is performed by evaluation module **345** and vpsnr module **370**, although some or all of the method can be performed by other modules in other embodiments.

The evaluation module **345** receives **600** coefficients $\hat{x}_k$ and $\hat{y}_k$. Coefficient $\hat{x}_k$ represents a set of transform domain coefficients of the original image **100**. Coefficient $\hat{y}_k$ represents a set of transform domain coefficients of the distorted image **110**. In one embodiment, one set of transform domain coefficients $\hat{x}_k$ of original image **100** and one set of transform domain coefficients $\hat{y}_k$ of distorted image **110** correspond to each non-overlapping pixel image block. The evaluation module **345** then computes **610** the transform domain mse, variance of the set of coefficients of the original image **100** (σ_x^2), and variance of the set of coefficients of the distorted image **110** (σ_y^2) for one or more blocks in the image.

In one embodiment, the transform domain mse is defined as:

$$mse = \frac{1}{n}\sum_{k=0}^{n-1}(x_k - \hat{y}_k)^2 \tag{1}$$

In equation (1), k is used as an index for transform domain coefficients in an image block, and n represents the total number of transform domain coefficients in an image block of a frame. Thus, in this embodiment, the mse is quadratic and is captured over a set of indices k by summing the squared difference between the transform domain coefficients of an original image **100** block and the associated transform domain coefficients of a corresponding distorted image **110** block, and dividing by n.

In one embodiment, the transform domain variance of the coefficients $\hat{x}_k$ of an original image **100** block is defined as:

$$\sigma_x^2 = \frac{1}{n-1}\sum_{k=1}^{n-1}(\hat{x}_k)^2 \tag{2}$$

Similarly, the transform domain variance of the coefficients $\hat{y}_k$ of a distorted image **110** block is defined as:

$$\sigma_y^2 = \frac{1}{n-1}\sum_{k=1}^{n-1}(\hat{y}_k)^2 \tag{3}$$

Variances σ_x^2 and σ_y^2 are quadratic and captured over a set of indices k by summing the squared transform domain coefficients for an original image **100** block and distorted image **110** block and dividing by n−1.

Adaptation constants a and b are selected **620** to increase the correlation between the computed visual quality measure and human perception. In one embodiment, a and b are selected to increase correlation with human perception of JPEG-compressed images. In one embodiment, correlation with human perception is determined by measuring the visual quality of encoded images retrieved from the Tampare Image Database, a database comprising 25 reference images and 1700 distorted images and various distortion levels optimized for visual quality comparison, and comparing the visual quality measurement to human perception marks stored in the database associated with the images. In one embodiment, for 4×4 and 8×8 pixel blocks, the adaptation constants are selected so that a=2 and b=1. The adaptation constants may be selected by evaluation module **345**, by vpsnr module **370**, or by any other module. More information on the Tampare Image Database may be found, for example, at http://www.ponomarenko.info/tid2008.htm.

The vmse is computed **630** for an image block by vpsnr module **370**. In one embodiment, the vmse for an image block is defined as:

$$vmse = \frac{a \cdot mse}{a + b \cdot \sqrt{\sigma_x \sigma_y}} \tag{4}$$

The vpsnr is next computed **640** by the vpsnr module **370**. In one embodiment, the vpsnr is defined as:

$$vpsnr = 10 \times \log_{10}\left(\frac{(2^N - 1)^2}{\overline{vmse}}\right) \tag{5}$$

In equation (5), N represents the number of bits used to represent a pixel per sample. In one embodiment, 8-bit samples are used, and $2^N-1=255$. Further, $\overline{\text{vmse}}$ is the mean of vmse values for all image blocks in the image.

In one embodiment, the computed vpsnr is outputted as the visual quality measure **160**. In alternative embodiments, the computed vpsnr may be manipulated, such as by converting the vpsnr into a different unit of measurement prior to being outputted as the visual quality measure **160**. Further, the vpsnr for multiple images may be computed and may be averaged prior to being outputted as visual quality measure **160**.

FIG. **7** is a flowchart illustrating a method of determining the visual quality of video in the pixel domain, according to one embodiment. In one embodiment, the method of FIG. **7** is performed by evaluation module **345** and vpsnr module **370**, although some or all of the method can be performed by other modules in other embodiments.

The evaluation module **345** receives **700** x_k and y_k. x_k represents a set of pixel values of the original image **100**. y_k represents a set of pixel values of the distorted image **110**. In one embodiment, one set pixel values x_k of original image **100** and one set of pixel values y_k of distorted image **110** correspond with each non-overlapping pixel image block. The evaluation module **345** next computes **710** the pixel value means $\overline{x}$ of an original image **100** block and the pixel value means $\overline{y}$ of a distorted image **110** block for one or more image block.

The evaluation module **345** then computes **720** the pixel domain mse, variance of pixel values of the original image **100** (σ_x^2), and variance of pixel values of the distorted image **110** (σ_y^2) for one or more blocks in the image. In one embodiment, the pixel domain mse is defined as:

$$mse = \frac{1}{n}\sum_{k=0}^{n-1}(x_k - y_k)^2 \tag{6}$$

In equation (6), k represents an index for pixels in a non-transformed image block, and n represents the total number of pixels in an image block of a frame. Thus, in this embodiment, the mse is quadratic and is captured over a set of indices k by summing the squared difference between the pixel values of an original image **100** block and the associated pixel values of an associated distorted image **110** block, and dividing by n, the total number of pixels for the block.

In one embodiment, the pixel domain variance of the pixel values of an original image **100** block is defined as:

$$\sigma_x^2 = \frac{1}{n-1}\sum_{k=0}^{n-1}(x_k - \overline{x})^2 \tag{7}$$

Similarly, the pixel domain variance of the pixel values of a distorted image **110** block is defined as:

$$\sigma_y^2 = \frac{1}{n-1}\sum_{k=0}^{n-1}(y_k - \overline{y})^2 \tag{8}$$

Variances σ_x^2 and σ_y^2 are quadratic and captured over a set of indices k by summing the squared differences between pixel values and pixel value means for an original image **100** block and distorted image **110** block, and dividing by n−1.

Adaptation constants a and b are selected **730** to increase the correlation between the computed visual quality measure and human perception. As discussed above, a and b may be selected to increase correlation with the human perception of JPEG-compressed images and correlation with human perception is determined by measuring the visual quality of encoded images retrieved from the Tampare Image Database. The vmse may be computed **740** for an image block using equation (4) and the vpsnr may be computed for the image using equation (5).

FIG. **8** is a flowchart illustrating a method of determining the visual quality of video in a prediction mode, according to one embodiment. In the event that neither pixel domain information nor transform domain information are available for a distorted image **110**, it is possible to estimate visual quality **160** by transforming the original image **100**, and analyzing the transformed original image and a corresponding transformed residual image **415**. The operating mode of this method is referred to herein as the prediction mode. In one embodiment, the method of FIG. **8** is performed by evaluation module **345** and vpsnr module **370**, although some or all of the method can be performed by other modules in other embodiments.

The evaluation module **345** receives **800** the quantization thresholds t_k and quantization invariants I_k^L, described above in detail with reference to FIG. **3**. In addition, the evaluation module **345** receives **800** variances σ_x^2 and μ_k. In one embodiment, the variances σ_x^2 may be calculated by transformation module **315** in the transform or pixel domains with equation (2) or equation (7). In one embodiment, standard deviations μ_k are the standard deviations of coefficients within blocks of the transformed residual image **415**. In one embodiment, evaluation module **345** receives the coefficients of the transformed original image **100** and transformed residual image **415** and computes variances a and standard deviations μ_k.

The evaluation module **345** estimates **810** the mse, and the variance of a distorted image **110** block (σ_y^2) for one or more blocks in the image. In one embodiment, the mse is estimated as:

$$mse \approx \frac{1}{n}\sum_{k=0}^{n-1}\mu_k^2 + \frac{1}{n}\sum_{k=0}^{n-1}Q_k^2 \cdot \left(2t_k - 1 - \sqrt{2} \cdot \frac{\mu_k}{Q_k}\right) \cdot \frac{e^{\sqrt{2}\frac{Q_k \cdot t_k}{\mu_k}}}{e^{\sqrt{2}\frac{Q_k}{\mu_k}} - 1} \tag{9}$$

In equation (9), k represents an index for coefficients in an image block, and n represents the total number of coefficients in an image block.

In one embodiment, the variance of a distorted image **110** block is estimated as:

$$\sigma_y^2 \approx \sigma_x^2 + \frac{1}{n-1}\sum_{k=1}^{n-1}\mu_k^2 + \frac{1}{n-1}\sum_{k=1}^{n-1} Q_k^2 \cdot \left(2t_k - 1 - \sqrt{2}\cdot\frac{\mu_k}{Q_k}\right)\cdot\frac{e^{\sqrt{2}\frac{Q_k \cdot t_k}{\mu_k}}}{e^{\sqrt{2}\frac{Q_k \cdot t_k}{\mu_k}} - 1} \tag{10}$$

Adaptation constants a and b are selected **820** to increase the correlation between the computed visual quality measure and human perception. As discussed above, a and b may be selected to increase correlation with the human perception of JPEG-compressed images and correlation with human perception is determined by measuring the visual quality of encoded images retrieved from the Tampare Image Database. The vmse estimate may be computed **740** for an image block using equation (4) and the vpsnr estimate may be computed for the image using equation (5).

The estimated values of mse and σ_y^2 do not require access to the distorted image **110**, or even require creating a compressed image **305**. Accordingly, the associated computed visual quality **160** does not require creating a compressed image **305**. As a result, it is possible to produce an estimate of image visual quality **160** prior to or independent of encoder **300** receiving the original image **100** for encoding. In one embodiment, this "offline" visual quality **160** prediction is used in conjunction with determining visual quality **160** in pixel mode or transform mode. In one embodiment, predicting visual quality **160** for an original image **100** allows rate distortion control module **440** to adjust encoder **300** performance prior to encoding original image **100**.

Example Visual Quality Determination Operating Modes

Table 1 displays the correlation with human perception for vpsnr and other measurements of visual quality. The correlation values for the alternative measurements of visual quality were obtained using the Tampare Image Database v1.0 (TID2008). The correlation value for vpsnr was computed and compared against the 25 reference images and the 1700 distortion images from TID2008. All measures of visual quality in Table 1 are with reference to JPEG and JPEG2000 formats.

TABLE 1

VPSNR VS. ALTERNATIVE MEASURES OF VISUAL QUALITY

Measure	Correlation with Human Perception
vpsnr	0.95
vif	0.75
vsnr	0.70
ssim	0.64
psnr	0.52

Embodiments described herein allow the visual quality of processed images to be measured in a way that correlates better with human perception than other measures. As is evidenced in Table 1, vpsnr outperforms Visual Information Fidelity ("vif"), Visual Signal-to-Noise Ratio ("vsnr"), Structural Similarity Index Metric ("ssim"), and psnr in correlating with human perception. Further, the computations associated with implementing the embodiments are significantly less resource intensive than other methods which measure an image's visual quality. The visual quality measure can be used in a feedback loop of an image processor to improve the quality of image processing, as described above with regards to FIG. **4**.

The above description is included to illustrate the operation of certain embodiments and is not meant to limit the scope of the disclosure. The scope of the disclosure is to be limited only by the following claims. From the above discussion, many variations will be apparent to one skilled in the relevant art that would yet be encompassed by the spirit and scope of the disclosure.

Some portions of above description describe the embodiments in terms of algorithmic descriptions and processes. These operations (e.g., the processes described above), while described functionally, computationally, or logically, are understood to be implemented by computer programs or equivalent electrical circuits, microcode, or the like. The computer programs are typically embedded as instructions that can be stored on a tangible computer readable storage medium (e.g., flash drive disk, or memory) and are executable by a processor. Furthermore, it has also proven convenient at times, to refer to these arrangements of operations as modules, without loss of generality. The described operations and their associated modules may be embodied in software, firmware, hardware, or any combinations thereof.

As used herein any reference to "one embodiment" or "an embodiment" means that a particular element, feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

Some embodiments may be described using the expression "coupled" and "connected" along with their derivatives. For example, some embodiments may be described using the term "connected" to indicate that two or more elements are in direct physical or electrical contact with each other. In another example, some embodiments may be described using the term "coupled" to indicate that two or more elements are in direct physical or electrical contact. The term "coupled," however, may also mean that two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other. The embodiments are not limited in this context.

As used herein, the terms "comprises," "comprising," "includes," "including," "has," "having" or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, "or" refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

In addition, use of the "a" or "an" are employed to describe elements and components of the embodiments herein. This is done merely for convenience and to give a general sense of the invention. This description should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise.

Upon reading this disclosure, those of skill in the art will appreciate still additional alternative structural and functional designs for a system and a process for providing a better measure of visual quality through the disclosed principles herein. Thus, while particular embodiments and applications have been illustrated and described, it is to be understood that the disclosed embodiments are not limited to the precise construction and components disclosed herein. Various modifications, changes and variations, which will be apparent to those skilled in the art, may be made in the arrangement, operation and details of the method and apparatus disclosed herein without departing from the spirit and scope defined in the appended claims.

The invention claimed is:

1. A method of measuring a visual quality of a processed image, comprising:

receiving a first image and a second image, wherein the second image is a processed version of the first image;

for each block in the first image, estimating a mean square error between the block in the first image and a block in the second image corresponding to the block in the first image based on quantization thresholds and quantization invariants used by an encoder;

determining a first set of variances of pixel values in a pixel domain or transform coefficients in a transform domain for each block in the first image;

estimating a second set of variances of pixel values or transform coefficients for each block in the second image based on the quantization thresholds and quantization invariants used by the encoder; and

computing a measure of the visual quality of the second image based at least in part on the estimated mean square errors, the first set of variances and the second set of variances.

2. A method of measuring a visual quality of a processed image, comprising:

receiving a first image and a second image, wherein the second image is a processed version of the first image;

estimating a measure of discrepancy between at least one block in the first image and at least one block in the second image corresponding to the at least one block in the first image based on quantization thresholds and quantization invariants used by an encoder;

determining a first set of variances of pixel values in a pixel domain or transform coefficients in a transform domain for the at least one block in the first image;

estimating a second set of variances of pixel values or transform coefficients for the at least one block in the second image corresponding to the at least one block in the first image based on the quantization thresholds and quantization invariants used by the encoder; and

computing a measure of the visual quality of the second image based at least in part on the measure of discrepancy, the first set of variances and the second set of variances.

3. The method of claim **2**, wherein the measure of the visual quality of the second image is computed based further on computing a measure of visual quality for more than one image block, and averaging the measures of the visual quality for the more than one image block to obtain the measure of the visual quality of the second image.

4. The method of claim **3**, wherein computing the measure of the visual quality of the second image is based further on at least adaptation constants and the number of bits per sample that represent each image pixel, wherein adaptation constants are selected to increase the correlation between the measure of visual quality of the second image and human perception of the second image.

5. The method of claim **2**, wherein estimating the measure of discrepancy comprises determining mean square errors between the at least one block in the first image and the at least one block in the second image corresponding to the at least one block in the first image.

6. The method of claim **2**, wherein estimating the measure of discrepancy and the first and second sets of variances comprises computing the measure of discrepancy and the first and second sets of variances based on the transform domain coefficients of the image blocks.

7. The method of claim **2**, wherein determining the measure of discrepancy and the second set of variances further comprises estimating the measure of discrepancy and the second set of variances based on the first set of variances and standard deviations of transform domain coefficients of residual image blocks.

8. The method of claim **7**, wherein the estimation of the measure of discrepancy is performed independently of the second image.

9. The method of claim **2**, wherein the measure of visual quality is used by an image processor to alter the processing of future images in a video sequence.

10. A system for measuring a visual quality of a processed image, the system comprising:

an evaluation module configured to:

receive a first image and a second image, wherein the second image is a processed version of the first image;

estimate a measure of discrepancy between at least one block in the first image and at least one block in the second image corresponding to the at least one block in the first image based on quantization thresholds and quantization invariants used by an encoder;

determine a first set of variances of pixel values in a pixel domain or transform coefficients in a transform domain for the at least one block in the first image;

estimate a second set of variances of pixel values or transform coefficients for the at least one block in the second image corresponding to the at least one block in the first image based on the quantization thresholds and quantization invariants used by the encoder; and

compute a measure of the visual quality of the second image based at least in part on the measure of discrepancy, the first set of variances and the second set of variances.

11. The system of claim **10**, wherein the measure of the visual quality of the second image is computed based further on computing a measure of visual quality for more than one image block, and averaging the measures of the visual quality for the more than one image block to obtain the measure of the visual quality of the second image.

12. The system of claim **11**, wherein computing the measure of the visual quality of the second image is based further on at least adaptation constants and the number of bits per sample that represent each image pixel, wherein adaptation constants are selected to increase the correlation between the measure of visual quality of the second image and human perception of the second image.

13. The system of claim **10**, wherein estimating the measure of discrepancy comprises determining mean square errors between the at least one block in the first image and the at least one block in the second image corresponding to the at least one block in the first image.

14. The system of claim **10**, wherein estimating the measure of discrepancy and the first and second sets of variances comprises computing the measure of discrepancy and the first and second sets of variances based on the transform domain coefficients of the image blocks.

15. The system of claim **10**, wherein determining the measure of discrepancy and the second set of variances further comprises estimating the measure of discrepancy and the second set of variances based on the first set of variances and standard deviations of transform domain coefficients of residual image blocks.

16. The system of claim **15**, wherein the estimation of the measure of discrepancy is performed independently of the second image.

17. The system of claim **10**, wherein the measure of visual quality is used by an image processor to alter the processing of future images in a video sequence.

18. A non-transitory computer-readable storage medium storing executable computer program instructions for measuring a visual quality of a processed image, the instructions comprising instructions for:

receiving a first image and a second image, wherein the second image is a processed version of the first image;

estimating a measure of discrepancy between at least one block in the first image and at least one block in the second image corresponding to the at least one block in the first image based on quantization thresholds and quantization invariants used by an encoder;

determining a first set of variances of pixel values in a pixel domain or transform coefficients in a transform domain for the at least one block in the first image;

estimating a second set of variances of pixel values or transform coefficients for the at least one block in the second image corresponding to the at least one block in the first image based on the quantization thresholds and quantization invariants used by the encoder; and

computing a measure of the visual quality of the second image based at least in part on the measure of discrepancy, the first set of variances and the second set of variances.

19. The non-transitory computer-readable storage medium of claim **18**, wherein the measure of the visual quality of the second image is computed based further on computing a measure of visual quality for more than one image block, and averaging the measures of the visual quality for the more than one image block to obtain the measure of the visual quality of the second image.

20. The non-transitory computer-readable storage medium of claim **19**, wherein computing the measure of the visual quality of the second image is based further on at least adaptation constants and the number of bits per sample that represent each image pixel, wherein adaptation constants are selected to increase the correlation between the measure of visual quality of the second image and human perception of the second image.

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